

# All About PHOTOVOLTAIC

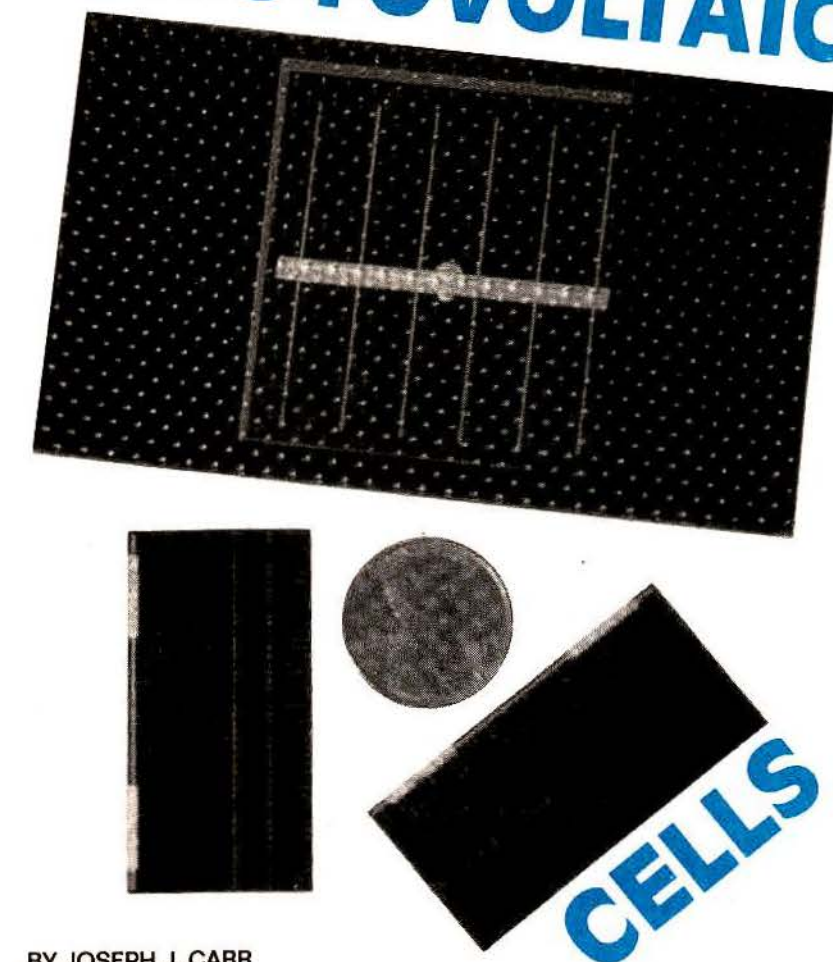
**A**lthough it may not be readily apparent from their limited use, photovoltaic cells can fill a large number of modern-day needs. For example, one fellow that I met at a hamfest served in a missionary medical unit in the Sudanese desert. He told me that they charge automobile batteries from solar-cells for their communications equipment and, he averred, "that comm equipment was vital, we could die without it."

Another chap I know owns a "traditional" sailboat, (i.e., one that has no electrical system. He generates battery power for his radio and navigation equipment using a solar-cell array.

Still another person I know created a small solar-powered three-home cable-TV system in the mountains of southwest Virginia. He needed 90 mA to run a wideband antenna amplifier at the head-end of a 800-foot long coaxial cable. The solution to the power problem was to use a 24-volt DC, 15-ampere-hour, gel-cell battery that is charged with a solar array that can produce nearly 1 ampere of DC when needed. This battery served for several years before needing service! If these examples make solar electric-power generation sound interesting, read on.

**A basic Cell.** A photovoltaic cell (also called photogalvanic cell or self-generating cell) is a device that generates an electrical potential when illuminated. Thus, if an illuminated photovoltaic cell is connected to a circuit, a current will flow from the cell through the circuit. The solar cell, which is used to generate electrical power, is perhaps the most common (or at least the most widely known) example of the photovoltaic cell. There are also instrumentation photovoltaic cells that are used to measure light levels rather than generate power.

Figure 1 shows three common symbols for the photovoltaic cell. The symbol in Fig. 1A is a standard PN diode symbol, with two arrows indicating light, aiming into it. This symbol is similar to that used for light emitting diodes (LED's), except for the direction of the two parallel arrows (in the LED symbol, the arrows are aimed outward, indicating an emitting device,



BY JOSEPH J. CARR

*Learn about photovoltaic cells and how you can better use them in your projects.*

as opposed to a sensor). It should be mentioned that this symbol typically denotes a "PN-junction" photovoltaic device (which we'll discuss later) in particular.

Another symbol is shown in Fig. 1B. This device is a battery symbol inside of a circle, with the greek letter lambda superimposed to indicate light sensitivity. We here at *Popular Electronics* use a symbol similar to both, shown in Fig. 1C.

**Metal/Semiconductor/Oxide Devices.** There are two broad classes of photovoltaic devices. The earliest

known group is formed from a metal/semiconductor bond. The other family is actually made up of special diodes.

In a metal/semiconductor device (like that shown in Fig. 2A), a metal disk of copper, gold, or platinum is coated with a layer of copper oxide, which is in turn covered with a semi-transparent layer of semiconductor material. The copper-oxide cell was invented prior to World War I by Bruno Lange, and eventually marketed by Westinghouse under the trade-name "Photax" cell.

A similar photovoltaic cell, made of

selenium, is shown in Fig. 2B. Cells like that were invented in the 1930's, and marketed by Weston Instruments under the trade name "Photronic" cell. In selenium cells, a thin layer of photosensitive selenium is coated onto an iron, steel, or aluminum plate.

In both forms of metal photovoltaic cell, the thin insulator (the copper-oxide or selenium) forms a barrier layer. When light illuminates the barrier layer, the impinging light photons are absorbed, and in the process free electrons are emitted. The existence of free electrons causes a difference of electrical potential to appear across the barrier layer.

As to the cells characteristics, the selenium layer is negative, while the thin metal side is positive. The cells produce an output potential in the range of 0.2- to 0.6-volts DC (0.45-volts DC with 2,000 foot-candles of illumination is a common standard). Photovoltaic cells designed for power applications produce between 20 and 90 milliwatts of DG power per square inch of photoactive surface exposed to light.

The selenium is sensitive to wavelengths from 300 to 700 nm, with its spectral response peaking near 560 nm. As with other sensors, it is common practice to alter the response of a selenium cell with special filters over the transparent window. For most instrumentation purposes, the selenium cell must be loaded with a resistor. Otherwise, it acts in a highly nonlinear manner.

**Silicon PN Junctions.** Perhaps one of the most successful forms of modern photovoltaic sensors is the PN-junction device. There are two recognized forms of PN photovoltaic sensors: heterojunction and homojunc-

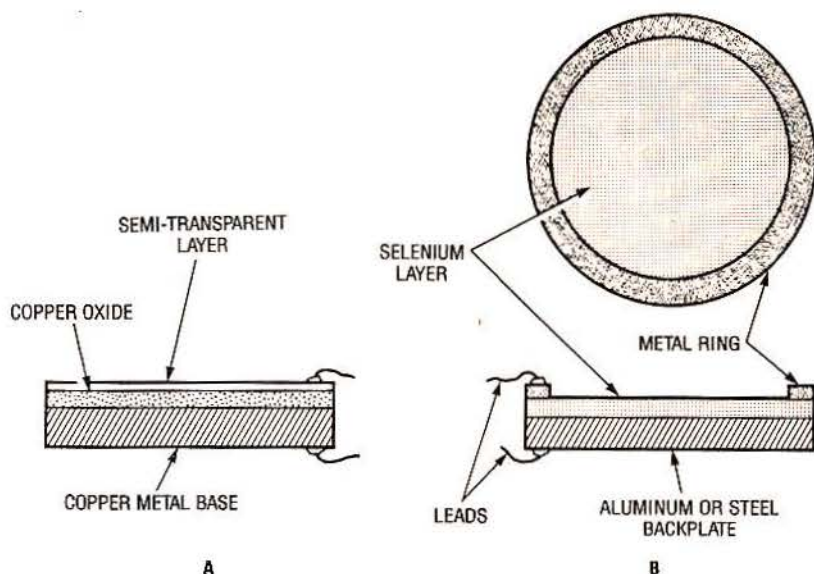


Fig. 2. Note how the oxide of the bottom layer of the metal/semiconductor-type cell in A is used as the middle layer. The selenium cell in B requires no middle layer.

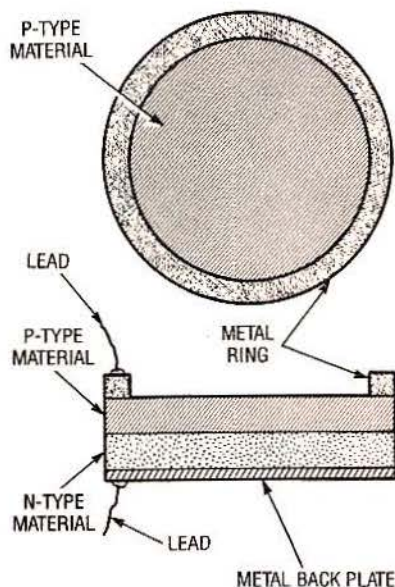


Fig. 3. PN-type cells look like metal/semiconductor cells in structure, but they are based on a standard PN junction.

The PN-junction photovoltaic cell works because there is an inherent electric field across the PN junction. When photons impinge on the PN junction, electron-hole pairs are created by the photons. The inherent electric field forces the positively charged holes to migrate towards the p-type material, and electrons to migrate to the n-type region. The migration results in an imbalance that creates a potential difference of several hundred millivolts. That potential is the open-circuit (no-load) voltage of the photovoltaic cell.

Figure 3 shows the structure of a silicon photovoltaic cell, which was discovered in 1958 by scientists working at Bell Telephone Laboratories. The silicon cell consists of a PN junction formed of P and N-type silicon. In the P-on-N form shown in Fig. 3A, a thin layer (about 0.5 mm) of arsenic-doped N-type silicon is deposited onto a metallic substrate to form the negative terminal of the cell. A P-type boron-doped layer is diffused into the silicon to form the surface to be exposed to light. The positive electrode is an annular ring deposited onto the exposed surface of the P-type silicon region. These cells output a potential of 0.27 to 0.6 volts under the illumination of 2,000 foot-candles. Response tends to peak at wavelengths around 900 nm.

An N-on-P silicon cell also exists in which a thin layer of phosphorous impurities are diffused into boron-

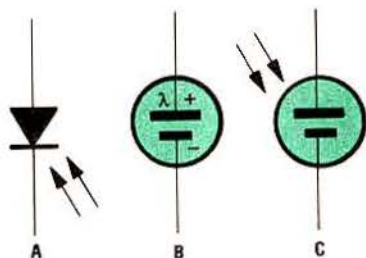


Fig. 1. These cell symbols are for a PN junction device (A), any photovoltaic cell (B), and any photovoltaic cell according to the style of this magazine (C).

tion. A heterojunction device uses two different materials to form a PN junction; an example is germanium/silicon (nGe-pSi) devices. Other types include thin-film pCu<sub>2</sub>-nCdS, pSi-nCdS, and pGe-nGaP devices. The latter two can be formulated to offer a wide response spectrum of 0.5 to 24μm. Most heterojunction devices were developed for solar power generation, but some are available as light sensors. Homojunction devices use but one type of material, of which the popular nSi-pSi device is an example.

doped p-type silicon. These cells show peak response near 800 nm.

To make a point, the spectral response of a "typical" silicon cell is shown in Fig. 4. Because of its response, the silicon photovoltaic cell is widely used in the visible-light region. The response is usable at ultraviolet wavelengths in the 400 nm range, but the response is quite poor, and exhibits a significant wavelength sensitivity. It peaks above 500 nm, and falls off gently to a wavelength around 900 nm, where it begins dropping off rapidly. As silicon only has a small amount of sensitivity in the near-infrared region, and none at all in the far infrared, different materials must be used for detecting IR wavelengths.

### Infrared Photovoltaic Sensors.

Infrared sensors are designed to be sensitive to electromagnetic radiation in the infrared (IR) region (i.e., at wavelengths longer than those of visible light). Because IR wavelengths can generate heat, it is sometimes necessary to cool IR sensors. Some sensors are operated at room temperature, which is about 27°C or 300°K (Note: 0°C = 273.16°K), but most of them require a cooler environment. A typical arrangement embeds the sensor in a Dewar flask (a dual-walled glass vacuum bottle) that is filled with liquid nitrogen to cool the sensor to 77°K. In other cases, dry-ice packs are used to cool the device to 196°K. Thermoelectric Peltier-effect cooling devices are also used. These devices are thermocouple piles made from dissimilar metallic or semiconductor sections that are excited by a DC current, causing one side to absorb heat, and the other to give up heat.

Germanium (Ge) is commonly used in IR-sensitive metal/semiconductor cells at room temperature (300°K). The material exhibits a somewhat narrow response centered around 1500 nm (i.e., 1.5  $\mu$ m).

Indium-Arsenide (InAs) (with the spectral response shown in Fig. 5) is also used. The InAs cell is used at 300°K, as well as colder temperatures down to 77°K. The impedance of this type of cell tends to vary with temperature, being around 100 ohms at 300°K and up to 10 megohms at 77°K. The response time of the InAs cell is on the order of 1  $\mu$ s.

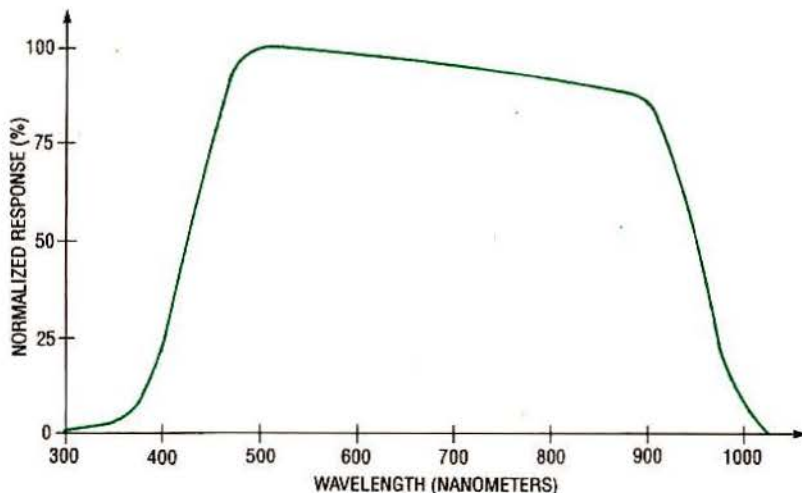


Fig. 4. As this generic silicon cell response shows, the cells have a bandwidth that's only usable over the visible-light spectrum.

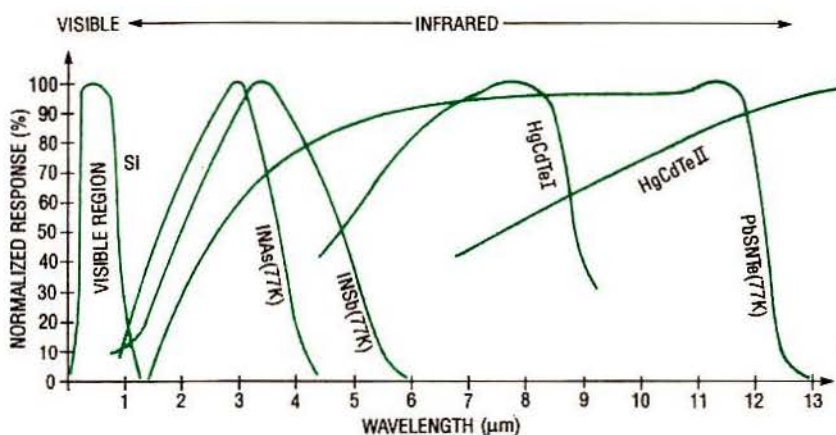


Fig. 5. Here we show the spectral response of different cells. Keep in mind that these are generic responses. Consult manufacturers literature for the response of specific products, as they may differ.

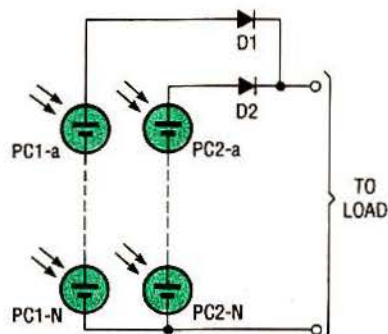


Fig. 6. When arrays of cells are connected in parallel to increase a system's overall current output, isolation diodes must be used.

Indium-Antimonide (InSb) is yet another material used. The InSb IR sensor offers a peak response at wavelengths around 3.5  $\mu$ m when operated at 77°K (see Fig. 5). It has a

response time similar to InAs cells (1  $\mu$ s). The impedance of those cells varies with temperature, similarly to InAs, but over a considerably smaller range (20k to 50k).

Lead-Tin-Telluride (PbSnTe) has applications in the far infrared region of the spectrum (from 6 to 15  $\mu$ m), and offers some response down to the near IR region around 2  $\mu$ m as shown in Fig. 5. This material operates at 77°K, with response times down to the 50 to 100 nanosecond (ns) range.

The last material we'll present, Mercury-Cadmium-Telluride (HgCdTe), can operate at temperatures between 77°K and 120°K, in a spectrum over a range of 2 to 14  $\mu$ m. Thus, HgCdTe cells can cover the entire IR spectrum from near-IR to far-IR. The actual response of any given cell can be custom tailored by changing

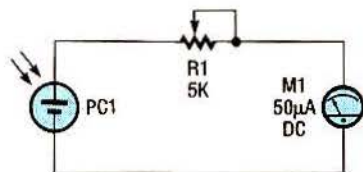


Fig. 7. Once calibrated, this simple light-meter circuit really works, and without the need for batteries.

the proportion of the three materials used (Hg, Cd, and Te). This phenomenon is shown in Fig. 5 by the two different HgCdTe curves labelled HgCdTe-I and HgCdTe-II.

### Photovoltaic-Cell Characteristics.

A photovoltaic cell is basically an electrical power source that converts light into voltage. It should not be surprising, therefore, to find that some of the characteristics of a photovoltaic cell are similar to the characteristics of other DC power supplies. Let's summarize them.

A cell's output voltage ( $V_{oc}$ ) is usually measured open-circuit style (i.e., with no load), and is defined as the output potential when the cell is illuminated by a standard 100-foot-candle light source. As mentioned before, the  $V_{oc}$  values for common photovoltaic cells are 0.2 to 0.45 volts for selenium cells, and 0.3 to 1.5 volts for silicon cells. Higher voltages can be produced by connecting two or more cells in series; cell arrays of 12 volts are common, while arrays of 24, 28, 32, and 120 volts are also available.

Because of internal resistance in the cell (see below), the output voltage drops from  $V_{oc}$  to a lower value called the "loaded output voltage" ( $V_o$ ) when current is drawn by an external load.

The output-current rating ( $I_o$ ) is the short-circuit current produced under standard illumination conditions (100 foot-candles). Selenium cells vary from around 15  $\mu$ A to almost 800  $\mu$ A per cell, while silicon cells vary from about 5 mA to almost 40 mA per cell. Current rating is increased in an array of solar cells by connecting two or more cells (or series-connected groups of cells) in parallel. A high-current array is shown in Fig. 6. In this case, two cell arrays are used (PC1 and PC2), and an isolation diode is used for each array.

All electrical current sources pos-

sess a certain inherent internal resistance or source resistance ( $R_s$ ). The resistance produces a voltage loss because a voltage drop is created across  $R_s$  when current is drawn, and this voltage drop must be deducted from the open-circuit output voltage in order to find the output voltage under load. The internal resistance can be calculated from:

$$R_s = V_{oc} / I_{sc}$$

where  $R_s$  is the internal resistance in ohms,  $V_{oc}$  is the open-circuit potential in volts, and  $I_{sc}$  is the short-circuit current in amperes.

Three factors affect the output power ( $P_o$ ) available from a specific photovoltaic cell: the illumination

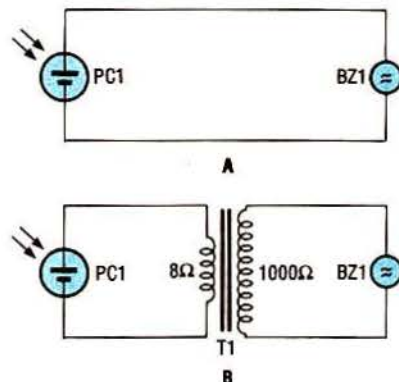


Fig. 8. It is possible to use photovoltaic cells to sound an alarm when the light level is high enough (A) or when a cell is pulsed (B).

level, the area exposed to the light, and the load resistance ( $R_L$ ). The output power can be found from any of the following:

$$\begin{aligned} P_o &= V_o I_o \\ P_o &= (V_o)^2 / R_L \\ P_o &= I_o^2 R_L \end{aligned}$$

The maximum power transfer between the photovoltaic cell and the load is found, as on any electrical power source, when the load resistance is matched to the internal resistance of the cell, or:

$$R_L = R_s$$

Now let's take a look at some applications circuits for photovoltaic devices, including both sensors and solar cells. Although the circuits use only one style of symbol, the same circuits work for PN-junction devices as well as metal/semiconductor devices.

**Instrumentation/Communications.** Of course, a power source is only useful if it can power something, and photovoltaic cells are no exception. That being so, let's take a look at some applications for the devices.

Figure 7 shows a cell in a basic light-meter circuit for use in photographic and other light-measurement applications. The photovoltaic cell is used to supply current to the circuit, which consists of a calibration resistor and a DC microammeter. The calibration resistor is adjusted to produce the desired meter deflection when exposed to some standard light-level.

Figure 8 shows two circuits that will work with small, low-voltage piezoelectric buzzers. These devices are widely used as annunciators in various applications, and are readily available at Radio Shack and similar outlets. When a photovoltaic cell is wired to a buzzer as shown in Fig. 8A,

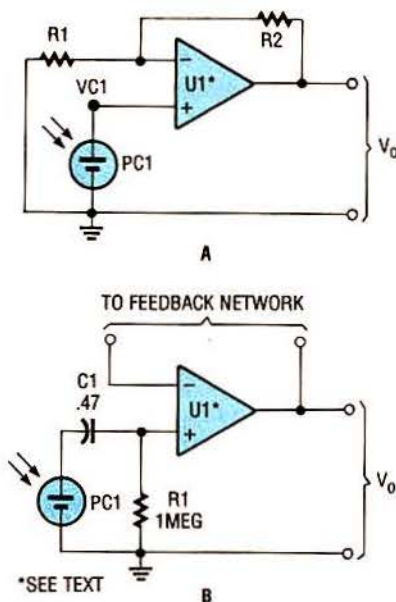


Fig. 9. You can use a photovoltaic cell to drive an operational amplifier so it will indicate the ambient light-level (A) or just changes in the ambient level (B).

the circuit acts as an alarm that will let the world know when the light level reaches a certain point (set by the characteristics of the components).

An alternate circuit, shown in Fig. 8B, makes use of a piezoelectric element (as opposed to a buzzer which consists of a piezoelectric element and on-board oscillator). The circuit can be used when the light level varies either naturally, is modulated, or is in-

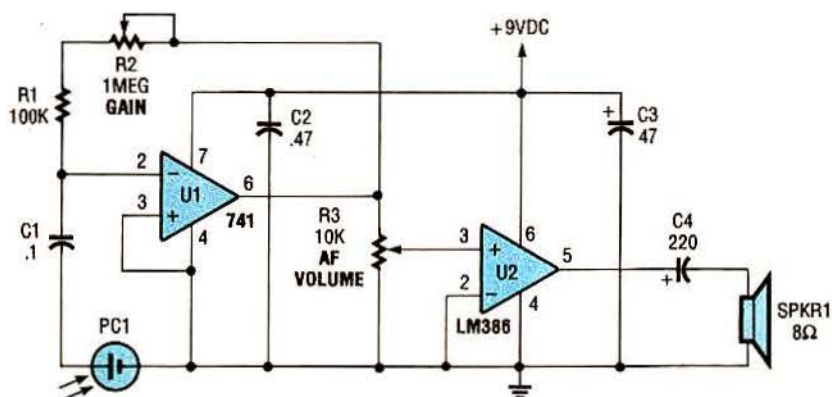


Fig. 10. This is an actual photovoltaic communications receiver. It demodulates AM light signals to recover the audio.

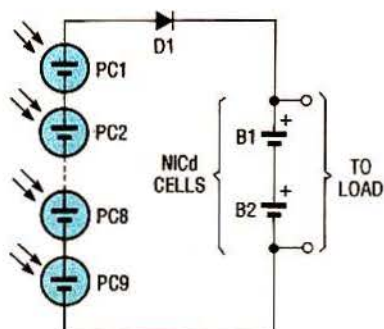


Fig. 11. Whenever a solar panel will be used to charge a battery, a diode must be used to keep the batteries voltage from reverse-biasing the cells.

tentionally chopped. The latter technique is often used in instrumentation applications, while modulation is useful for communications applications. The transformer is an output transformer intended for audio-amplifier circuits. The 8-ohm winding is normally used as the secondary, but here it is the primary; the 1000-ohm winding is used as the secondary. The use of the transformer in this manner produces a step-up action that will increase the voltage fluctuations caused by a varying light source. The principal application of such a circuit is in communications where a light beam is modulated by an audio signal.

One application of such AC-coupled circuits is in burglar alarms. If a pulsed light or IR source is used for the source, then only signals from that source will be passed to the secondary; ambient light will not affect the circuit. If an intruder attempts to defeat the alarm by shining a flashlight onto the cell, then the alarm would sound anyway. One would not use a

buzzer in that case, but rather a detector circuit that will indicate a break-in when the pulses disappear.

Figure 9A shows a typical circuit for instrumentation applications of the photovoltaic cell. The cell is connected across the input of a high impedance amplifier, such as the noninverting operational amplifier shown. The amplifier output voltage is

found from:

$$V_o = V_{C1}(R2/R1 + 1)$$

The operational amplifier provides a high input impedance buffer between the cell and whatever circuit follows it as well as providing voltage gain. The operational amplifier can be almost any common type, depending on the application. For most applications, common forms such as the 741, LM301, CA3140 (or their dual derivatives such as 1458, CA3240), etc.

An alternate connection scheme is shown in Fig. 9B. In the circuit the cell is AC-coupled, so it will not pass the static DC level created by ambient light, but rather only changing voltages caused by modulation of the light, chopping, or natural variations. When the light beam is truly static, the alternate circuit will not produce a signal.

A practical light-beam communications receiver is shown in Fig. 10. This circuit uses the AC-coupled variant of Fig. 9 with a 741 operational amplifier.

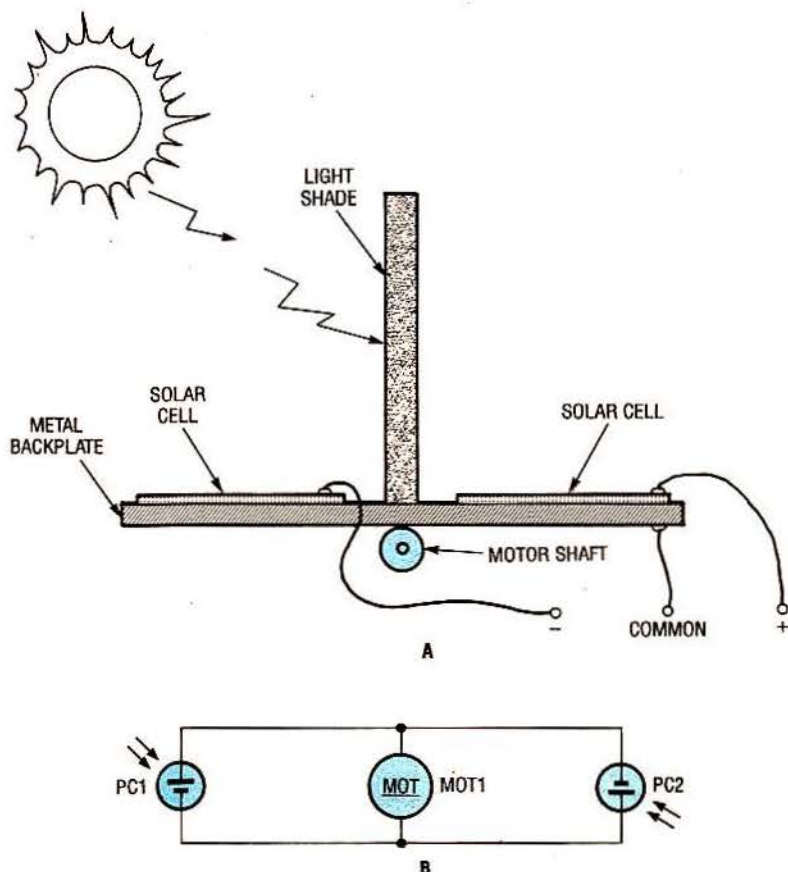


Fig. 12. Solar cells can be used to form a sun-tracking sensor array as shown in A. The cells must be connected to the positioning motor with opposing polarity as shown in B.

The circuit will operate from a any 9-volt DC power supply. The audio output stage is a single-chip audio amplifier that contains both preamplifier and power amplifier stages in one 8-pin DIP package. With the configuration shown, the LM386 will provide a gain of 20; if a higher gain (up to 200) is required, then connect a 10- $\mu$ F capacitor between pins 1 and 8 on the LM386. Two controls are provided in the circuit: the gain control, which controls the circuit sensitivity by varying the gain of the operational amplifier, and the volume control, which can be adjusted to produce a comfortable sound level.

**Other Applications.** One of the needs that photovoltaic cells fill is in the generation of DC electrical power from sunlight. These cells are used in a variety of power applications, but virtually all involve charging batteries from sunlight. The batteries can then power electronic equipment at night or when the sunlight fails. Examples include radio equipment in the tropics or deserts, on boats, or in remote sites where servicing fuel-run generators or running electrical power lines is a bother and thus costly.

The photo at the beginning of this article shows some basic solar cells designed for power generation. The two smaller units (a penny is provided for size comparison) are 0.45-volt, 40-mA devices, while the larger is a 70-mA, 1.5-volt flexible solar cell.

Figure 11 shows such an array being used to charge nickel-cadmium (NiCd) cells. The diode (D1) in series with the photovoltaic cells is used to prevent the NiCd cells from discharging through the photovoltaic cells (which would otherwise happen, especially when the light level is reduced). The type of diode shown here is satisfactory for very low current lev-

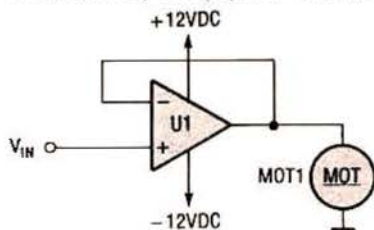


Fig. 13. A power op-amp can be used to drive a large solar panel's tracking motor. However, note that a dual supply is required.

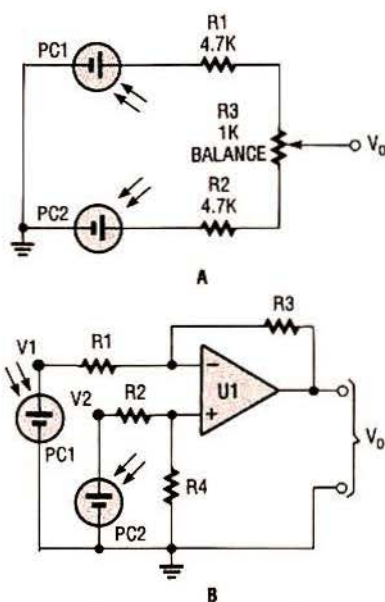


Fig. 14. Here are two solar cells in a summed-output circuit. The one in A is a passive circuit, while the one in B is an active version. The output voltage is proportional to the difference between cell output voltages.

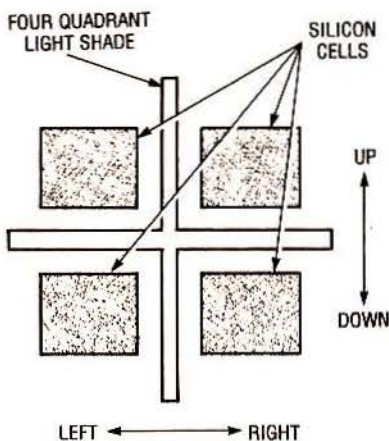


Fig. 15. Taking the two-cell tracker a step further results in this four-quadrant tracker. It is capable of following light by rotating along two axis.

els, but for larger arrays a diode with a larger current rating is required. Note: some arrays contain built-in diodes, so they do not require an external isolation diode.

One of the dangers of the circuit shown is the possibility of overcharging the battery during periods of prolonged sunlight. If that is a problem, then a voltage regulator can be inserted into the circuit in place of the isolation diode. The output voltage of the regulator is simply adjusted (with the battery disconnected) to the exact

voltage that will be expected when the battery is fully charged.

Another problem with solar-powered devices is that the sun does not stand still over the course of a day, or even follow the same course as the seasons change. It is sometimes necessary to mount the solar-cell array on a movable platform that is connected to a motor/tracker circuit. Figure 12 shows a sun-position tracker designed by writer Forrest Mims III in *Science Probe!* magazine (November 1990, p. 75). Two matched solar cells are mounted on a metal backplate that can be made from printed-circuit board stock.

A light shade painted flat black is mounted vertically on the backplate so that the sun will fall unevenly on the two sensors except when the panel is pointed directly at the sun. The two solar cells are connected with opposite polarity across a low-voltage DC motor, that is mechanically linked to a bearing sleeve on the underside of the backplate.

A potential problem with the simple circuit is that it will not drive a motor powerful enough for a large array. The problem can be overcome by using an outboard power supply (which may require its own solar array and battery set) to drive the necessary motor.

To provide an appropriate drive signal one could use a power operational amplifier as shown in Fig. 13. The  $V_{in}$  signal is derived from a differential sensor circuit, two of which are shown in Fig. 14. In both cases, the mechanical arrangement, shown in Fig. 12A, is used for mounting the sensors. The passive version, shown in Fig. 14A, uses a pair of solar cells whose output voltages are opposing each other, and combined together in a resistive summer circuit. The output voltage,  $V_o$ , will be zero when the two cells are equally illuminated because the two cells' contributions cancel each other out, but  $V_o$  will take on the polarity of the most highly illuminated cell when the light level is uneven.

Figure 14B shows a pair of cells applied to the inputs of a DC differential amplifier made from an op-amp. The voltage gain ( $A_v$ ) of the op-amp can be adjusted as needed by varying the ratios of the feedback and input resistors. The gain can be found from

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## NON-SERIOUS CIRCUIT

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fact and make sure that no solder is blocking the small hole in it.

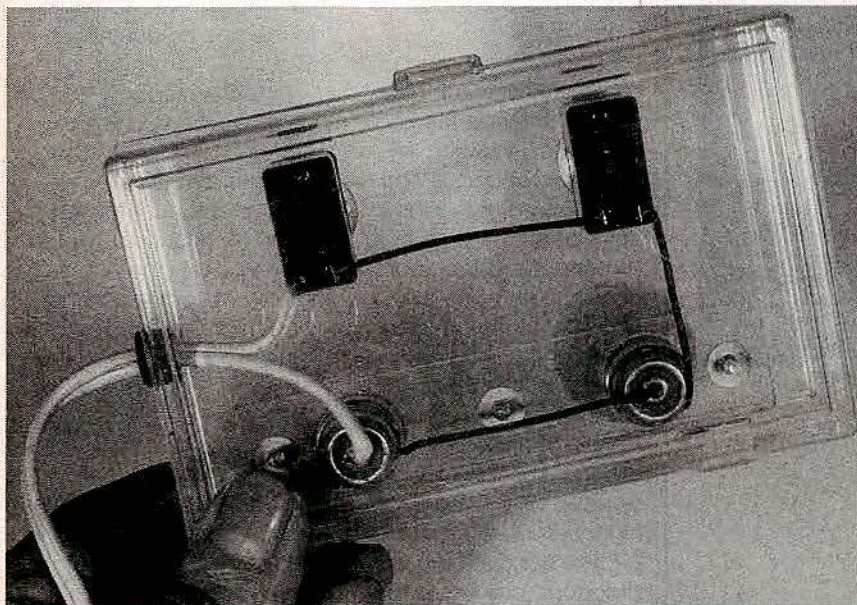
Apply a liberal coating of epoxy to the inside of the shell and install it on the base. The uncut lead from the diode goes through the hole in the end contact and the short length of hook-up wire through the small notch in the shell. Clamp the assembly together and allow the epoxy to set with the bulb in a base-up position.

When the adhesive has cured, sol-

If you are using a different type of switch or you cannot locate any diodes small enough to fit, you can probably find some space for the diode somewhere else in the switch housing. A motor tool with a small burr bit can be used to rout out space at the end of the housing opposite the contacts. Small wires can be used to connect the diode to the contacts.

Reassemble the switches, making sure that the slot in the mounting bushing is on the side opposite the contacts. This assures that the on-off nameplates will read correctly.

Mount the components in the box



The components of the circuit can be clearly seen through the transparent enclosure. Note the clear-plastic strip holding the socket shells in place beneath the box's cover.

der the diode lead to the end contact and cut it off flush. With your goggles on, clip off the other lead so that about  $\frac{1}{16}$  of an inch is exposed, bend it over, and solder it to the shell. Repeat the operation with the other lamp, but this time the cathode end of the diode should be left long for connection to the end contact.

Open up the toggle switches and, by pushing them out from the back, remove the contacts. If you use the same switches the author did, drill a small hole in the left-hand contact for one lead of the diode, and tin the area of the right-hand contact where the other lead will go. Reassemble the contacts into the switch housing and, with its leads cut short, solder the diode to the contacts. In one switch, the cathode should face to the left, in the other, to the right.

and make the connections as shown back in Fig. 2. Be careful to wire the unit properly with respect to the diodes. If, for example, you were to wire from the shell of one socket to the shell of the other socket, the DC would be routed through the diode in the wrong direction, resulting in its destruction when both switches were closed. Install the lamps and paint the switch handles to correspond to the colors of the bulbs.

**Using the Unit.** The best way to present the Non-Serious Circuit to a friend is to pretend to be confused. Explain that you'd like his help—it seems that you wired up this circuit and it is operating in a very strange manner. You can probably build the unit in one evening with parts already on hand, so I hope you'll give it a try.

## PHOTOVOLTAIC CELLS

(Continued from page 62)

the following equation:

$$A_v = R_3/R_1$$

if  $R_1 = R_2$  and  $R_3 = R_4$ . The output voltage from the operational diff-amp is:

$$V_o = (V_2 - V_1)R_3/R_1$$

The output of the differential amplifier is connected to the input of the circuit of Fig. 13. Note in Fig. 14B that the two cells are connected with the same polarity, but that the inputs of the differential amplifier have opposite polarities. When the two cells are equally illuminated, then the two voltages ( $V_1$  and  $V_2$ ) are equal, so by the last equation the output voltage is zero. Thus, the motor will not turn in either direction. But when the illumination is unequal,  $V_1$  and  $V_2$  are unequal, and the output voltage is proportional to the difference between  $V_1$  and  $V_2$ .

A crude four-quadrant light sensor is shown in Fig. 15. This sensor will detect a light's orientation along two axis. I've seen similar circuits used in toy cars and robots that will follow a light source. This sensor is used with two circuits like the one in Fig. 14B; one for the up/down motor and one for the left/right motor.

Photovoltaic sensors are readily available from sources such as Radio Shack, Edmund Scientific Co. (C918 Edscorp Building, Barrington, N.J., 08007; Tel. 609-547-8880) and Digi-Key (P.O. Box 677, Thief River Falls, MN, 56701; Tel. 800-344-4539). They are easy to use, and a lot of fun to experiment with.

